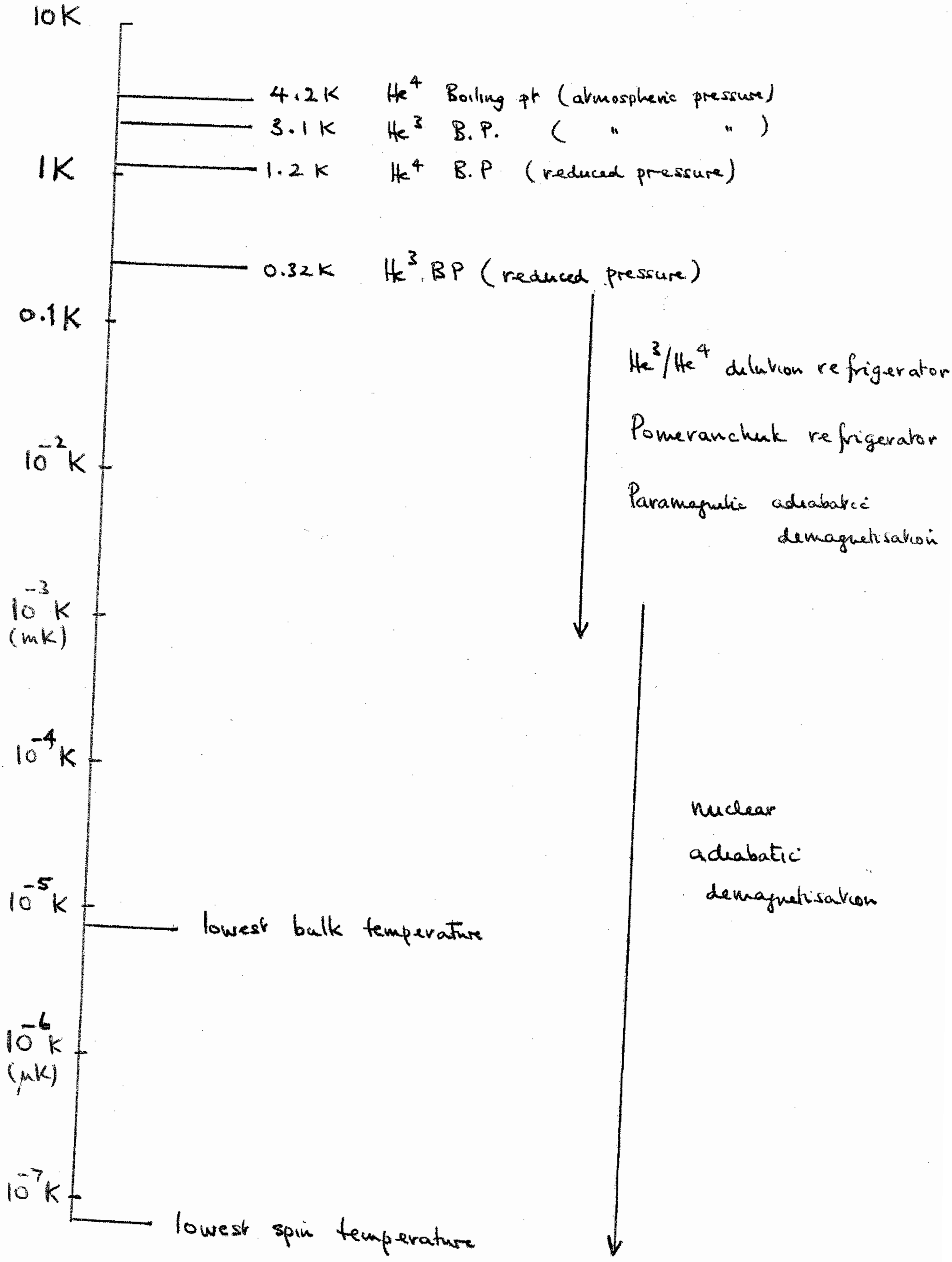
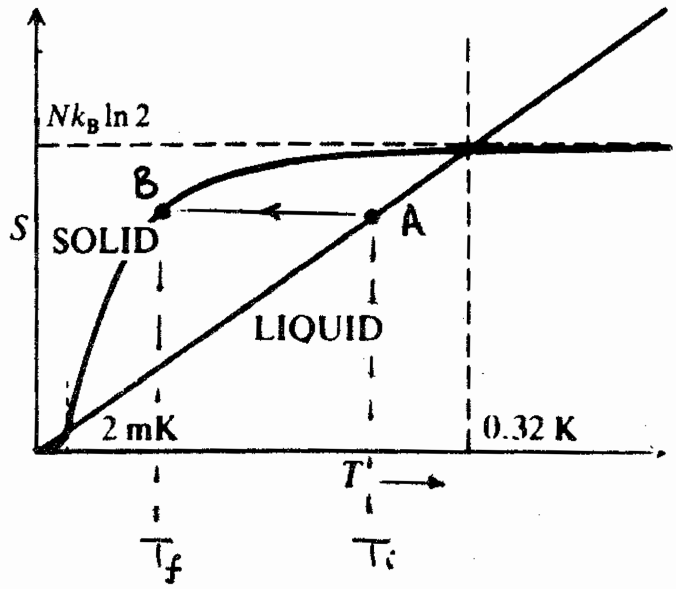
Low temperature scale and methods of cooling.



Cooling methods spanning 1K → 1mK.

1. Pomeranchuk cooling — Principle.

Working substance He^3

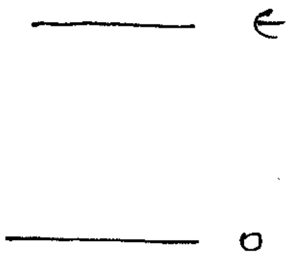


He^3 phase diagram in range 2mK → 0.32K shows entropy of liquid He^3 less than solid.

Occurs because disorder due mainly to nuclear spins — in solid (localised atoms) spin states populated according to Boltzmann statistics — because atoms are distinguishable (by site position).

In liquid (Fermi gas) Pauli principle imposes spin ↑↓ in each state

System of distinguishable atoms $S = \frac{1}{2}$



At temp T

Entropy

$$S = Nk \ln\left[1 + \exp(-\epsilon/kT)\right] + \frac{Nk\left(\epsilon/kT\right)\exp(-\epsilon/kT)}{\left[1 + \exp(-\epsilon/kT)\right]}$$

As $kT \gg \epsilon$

$$\exp(-\epsilon/kT) \to 1$$

$$S \to Nk \ln 2.$$

Method.

Initial state – quantity of liquid He^3 at $\sim 0.2\,K$

Compress adiabatically.

$$\text{Adiabatically} \equiv \left\{ \begin{array}{l} \text{at constant } S \\ \text{no energy flows in or out} \\ \text{of system.} \end{array} \right.$$

System of He^3 goes $A \longrightarrow B$ on diagram.

Temperature falls from $T_i \longrightarrow T_f$.

Takes place in compression cell – thermally insulated.

Any sample to be cooled – attached to cell.

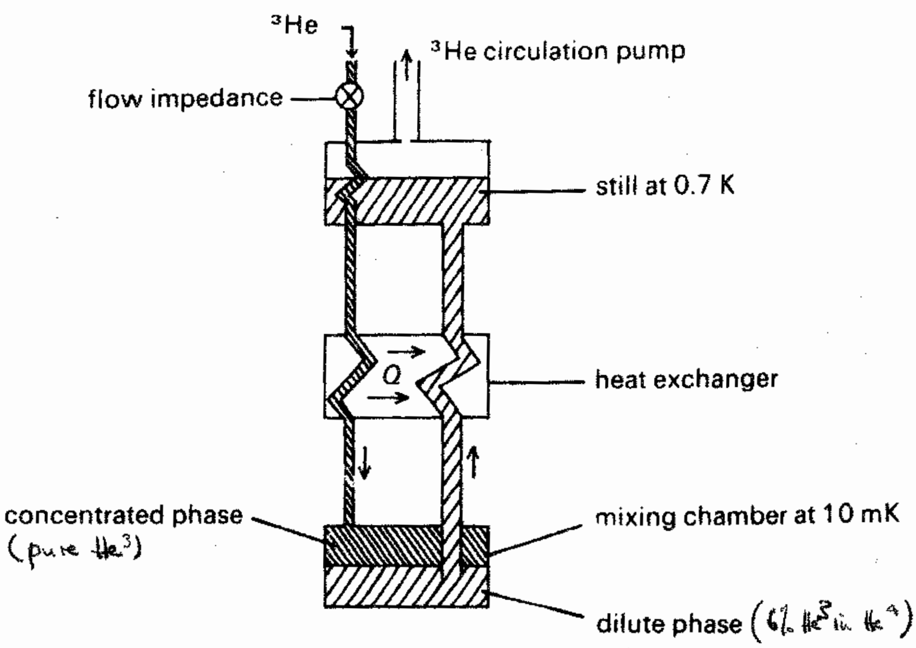
He^3 / He^4 dilution refrigerator.

Main method for cooling to ~ 1 mK.

Recall from study of He^3/He^4 liquid mixtures that at $T < 0.86$ K mixture of He^3 and He^4 forms phase separated system.

At $T \sim 0.2$ K — layer of pure He^3 floats on top of layer of ~ 6% He^3 in He^4.

Schematic diagram of refrigerator.



(195) Action of refrigerator.

Cooling caused in mixing chamber when atoms of pure (concentrated) He^3 cross phase boundary into 6% He^3 (dilute) phase.

Like evaporation from liquid to gas — heat removed from pure He^3 phase — causes temperature in mixing chamber to fall to mK.

To keep continuous cycle going

Dilute phase connected to still.

In still surface of liquid pumped — extracts He^3 atoms preferentially as gas

Gas circulated to pure He^3 input

Cooled through still (0.7 K)

Cooled through heat exchanger (mK)

and back into pure He^3 phase in mixing chamber

Any sample attached to mixing chamber.

(19b)

3. Paramagnetic adiabatic demagnetisation.

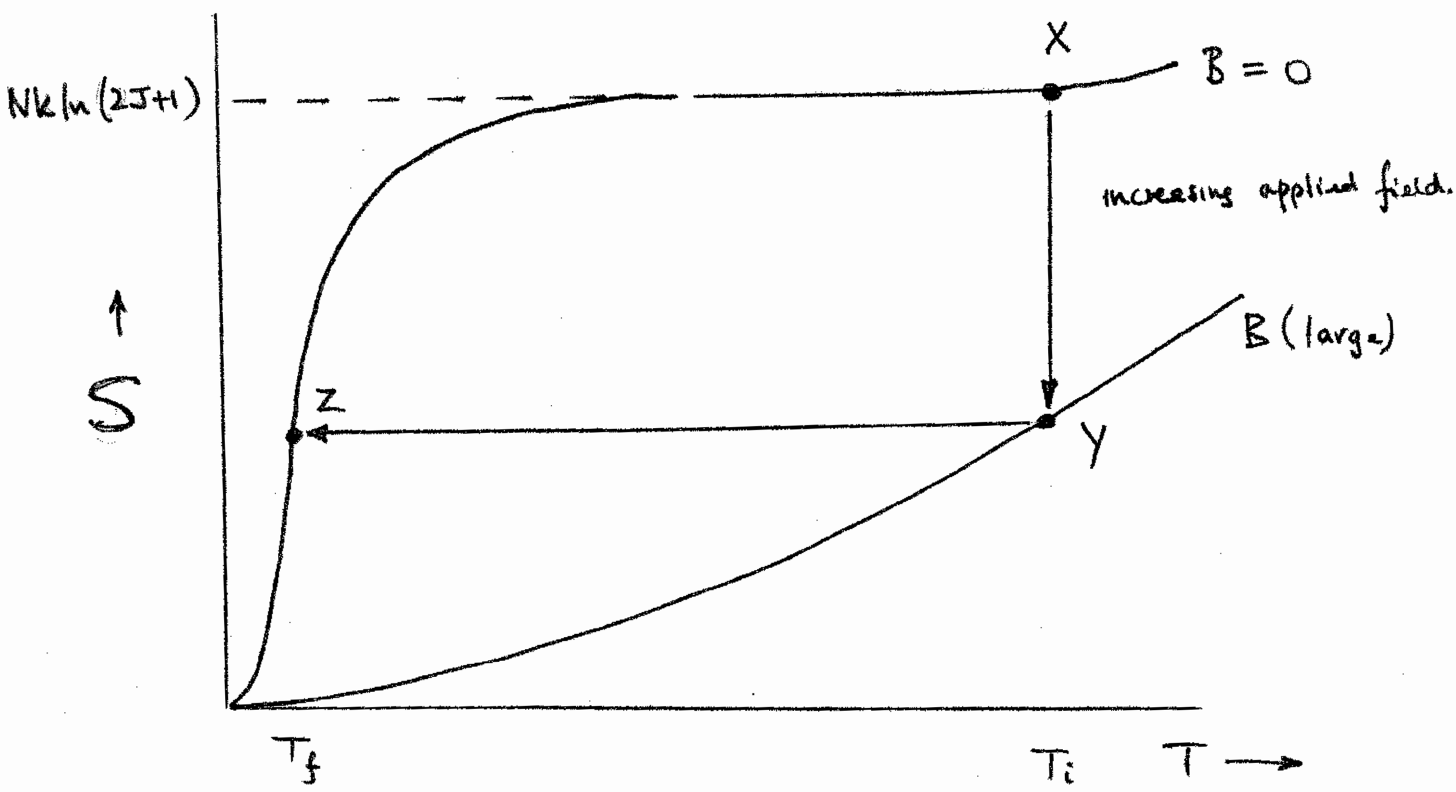
Method as described below – reaches mK.

Method spanning mK → μK.

Nuclear adiabatic demagnetisation

System – sample of metallic copper (Cu)

At mK starting temperature main cause of entropy (disorder) is random (quantised) orientations of nuclear spin J and associated magnetic moments.



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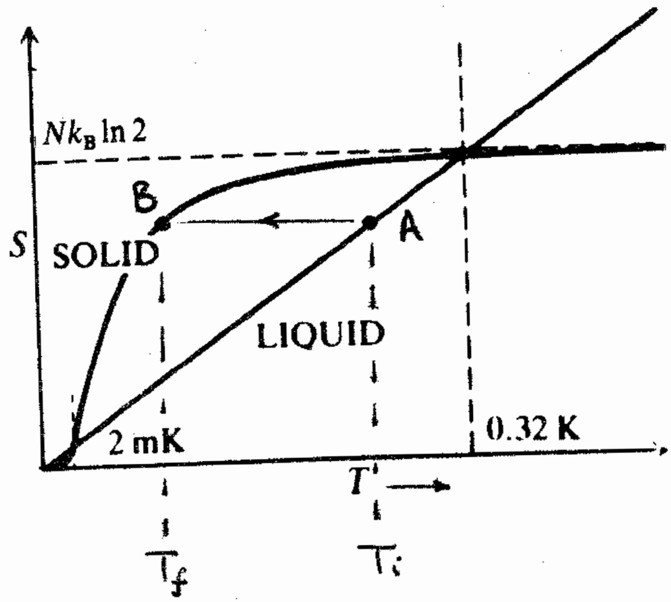

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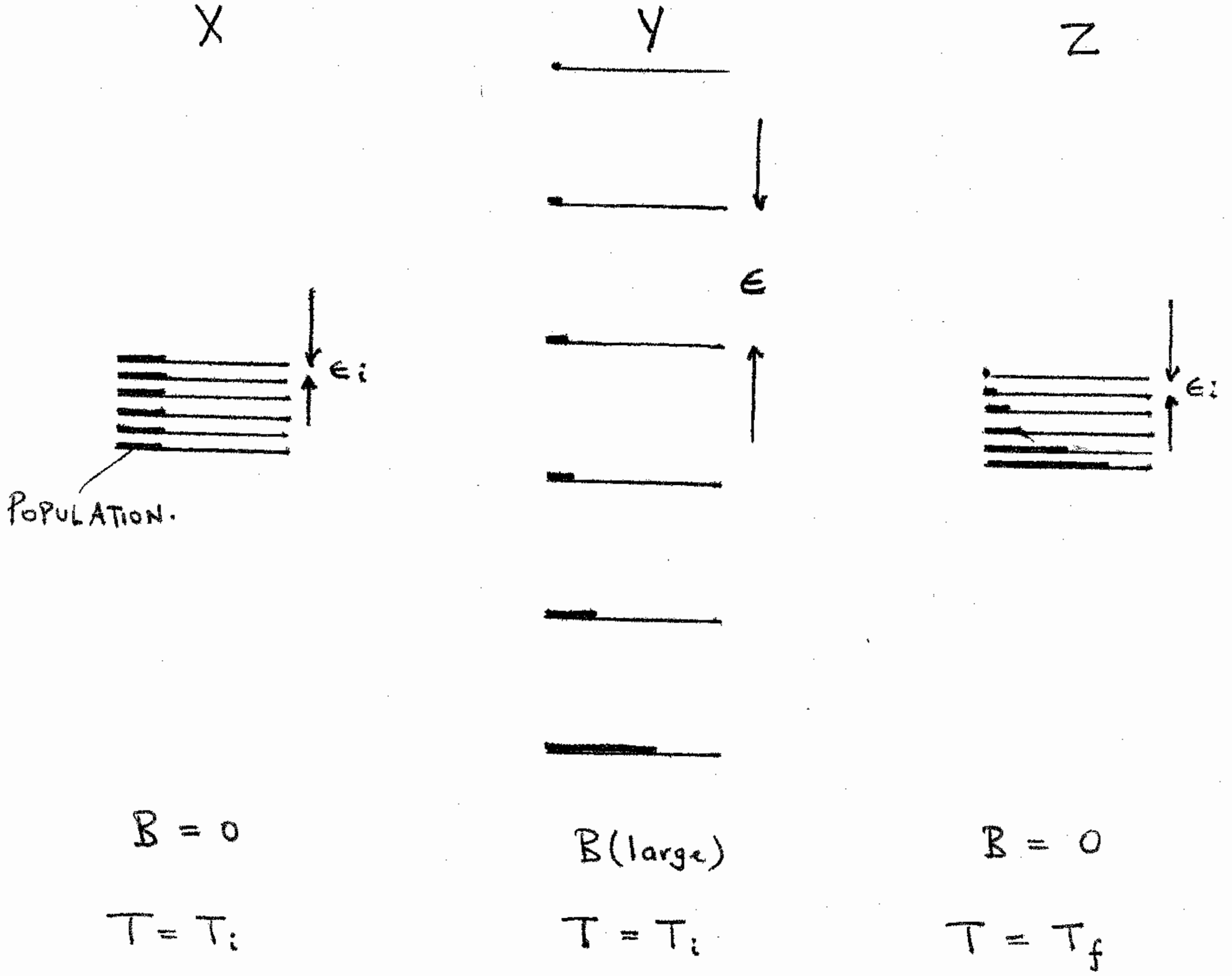
Nuclear Energy Levels.



Method

(i) Start at $T_i \sim 1$ mK

Energy levels of Cu nuclei have very small splitting ϵ_i

States approximately equally populated since $\epsilon_i \ll kT$

Hence $\exp(-\epsilon_i/kT) \sim 1$

(ii) Apply strong magnetic field B

Causes large splitting of energy levels. $\epsilon = g\mu_N B$

Now $\epsilon \gg kT$ thus $\exp(-\epsilon/kT) \ll 1$

Now population adjusts

Energy given out – since heavy population of low energy states.

Sample in contact with mK refrigerator – which takes this heat away.

Transition $X \to Y$ on diagram

(iii) Thermal contact between sample and mK refigerator broken.

Field B switched off adiabatically $\left\{\begin{array}{l}\text{no change in } S \\ \text{no energy flow in} \\ \text{or out of sample}\end{array}\right.$

Energy levels return to stage (i)

but with populations of stage (ii)

Means $\exp\left(-\epsilon_i/kT_f\right) \ll 1$

Hence $T_f \ll T_i$

Transition $Y \to Z$ on diagram

$T_f \sim \mu K.$

(199) What limits the final temperature T_f ?

In sample magnetic moments of Cu nuclei set up small internal magnetic field B_i

— This causes the splitting ϵ_i

When large external field B applied effective field

$$B_e = \{B^2 + B_i^2\}^{1/2}$$

In cooling transition $Y \rightarrow Z$

S is constant

but S is a function of (B/T) only

thus in $Y \rightarrow Z$ (B/T) is constant

Hence at Y $\dfrac{B_e}{T_i} = \dfrac{B_i}{T_f}$ ← at Z

and $T_f = T_i \dfrac{B_i}{B_e}$

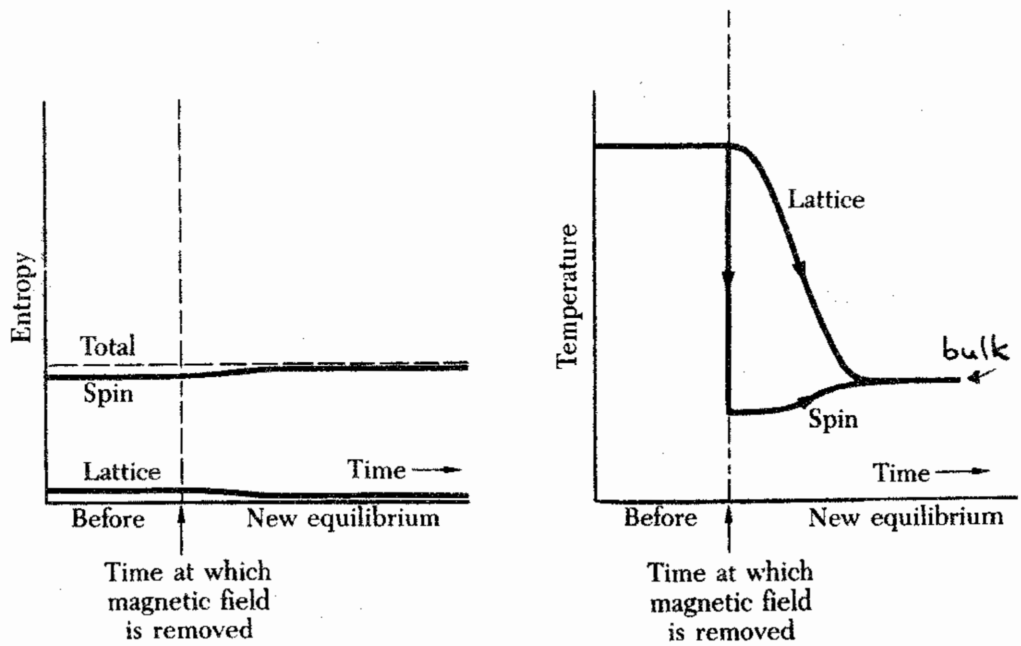
final temp.

Spin temperature / bulk temperature.

Method above cools spin system

To cool bulk of sample spin system and lattice must come to equilibrium. – energy passes from lattice to spins.

Schematic diagram



When spin and lattice in equilibrium – have achieved bulk cooling.

Can we go lower in temperature?

If system still has some disorder and you can affect this by applying some external condition (pressure, magnetic field..) then by reducing the entropy you can get to lower temperature

If there is no entropy left in the system that you can influence – then cannot lower temperature.